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Narrow linewidth short cavity Brillouin random laser based on Bragg grating array fiber and dynamical population inversion gratings

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ABSTRACT

We report on random lasing observed with 100-m-long fiber comprising an array of weak FBGs inscribed in the fiber core and uniformly distributed over the fiber length. Extended fluctuation-free oscilloscope traces highlight power dynamics typical for lasing. An additional piece of Er-doped fiber included into the laser cavity enables a stable laser generation with a linewidth narrower than 10 kHz.

In random laser cavities [1] the amplified photons scatter multiple times and do not return to their initial location periodically, so it is impossible to form a spatial resonance. Such regimes have been achieved in all-fiber laser configurations [2,3], where natural Rayleigh backscattering is used as a random distributed feedback. Here, we report on random lasing realized with the use of Brillouin amplification in a new fiber material, a FBG array fiber. Backscattering from multiple weak Bragg reflectors inscribed in the fiber core and uniformly distributed over the fiber length is employed instead of Rayleigh scattering. In contrast to previous experiments with 25-km standard telecom fibers [4], we use 100-m length of a single-mode fiber only demonstrating similar results. An additional nonlinear filter based on the population inversion dynamical gratings implemented into the fiber cavity with a piece of Er-doped fiber enables a stable laser generation with a linewidth narrower than 10 kHz.

The germanium-silicate fiber has been fabricated in IRE drawing facility. The fiber parameters are the following: the core diameter is 6 µm, the cladding diameter is 125 µm, the core/cladding refraction index step difference is ~0.025, the cutoff wavelength is 1350 nm, NA is ~0.27. Multiple weak reflectors (FBGs) have been inscribed in the fiber core by an excimer laser operating at 248 nm through a phase mask, in-situ, immediately during the fiber drawing process [5]. The peak reflectivity of a single reflector is estimated to be as low as ~0.001%. All reflectors are uniformly distributed over the fiber length with a step of ~1.1 cm. The total reflectivity measured with 100-m fiber length exhibits a 30% peak at 1552.02 nm with ~0.25 nm spectrum width (FWHM). The experimental configuration of the random laser is shown in Fig. 1(a). The fiber is pumped through an optical circulator from ~350mW narrow-band laser source that is 100 kHz 20-mW tunable Agilent continuous wave laser coupled with an erbium doped amplifier (EDFA). At the far end, the fiber is supplied by ~70% fiber Bragg grating (FBG) with ~70 pm reflectivity band centered at 1552.02 nm and adjusted for selective Brillouin wave reflection. In addition, the configuration could include a piece of low-doped erbium optical fiber of 1 m length, which is used as a nonlinear mode selector [6]. An optical isolator prevents Fresnel reflections from the far fiber end. Pumping of the fiber provides Brillouin amplification over the fiber length within the spectral band Stokes-side shifted by the Brillouin frequency shift Δ_{SBS} ~11 GHz from the pump frequency ν_L. In the beginning of the experiment the laser efficiency has been optimized by adjustment of the pump laser wavelength to make the Brillouin gain spectrum peak at $\nu_S = \nu_L - \Delta_{SBS}$ coincident with the peak of the FBG reflectivity. The laser radiation from the circulator output is filtered at ~1552.02 nm by ~70 pm pass FBG based filter and detected by high-speed photodiodes for recording by a digital oscilloscope and further analysis. The bandwidth of the recording scheme is 1.2 GHz. Besides, optical spectrum analyzer (OSA) with a spectral resolution of 0.01 nm is used for recording optical spectra from the circulator output. The laser could operate employing the distributed reflectors inscribed in the fiber and the external FBG [7,8]. Interaction between optical and acoustic waves inside the fiber is shown in Fig. 1(b). With laser pumping at ν_L the pump wave provides a gain for contra-propagating SBS Stokes wave at ν_S leading to efficient pump-to-Stokes wave power conversion. The Stokes wave reflected by the distributed gratings (R-Stokes) does not

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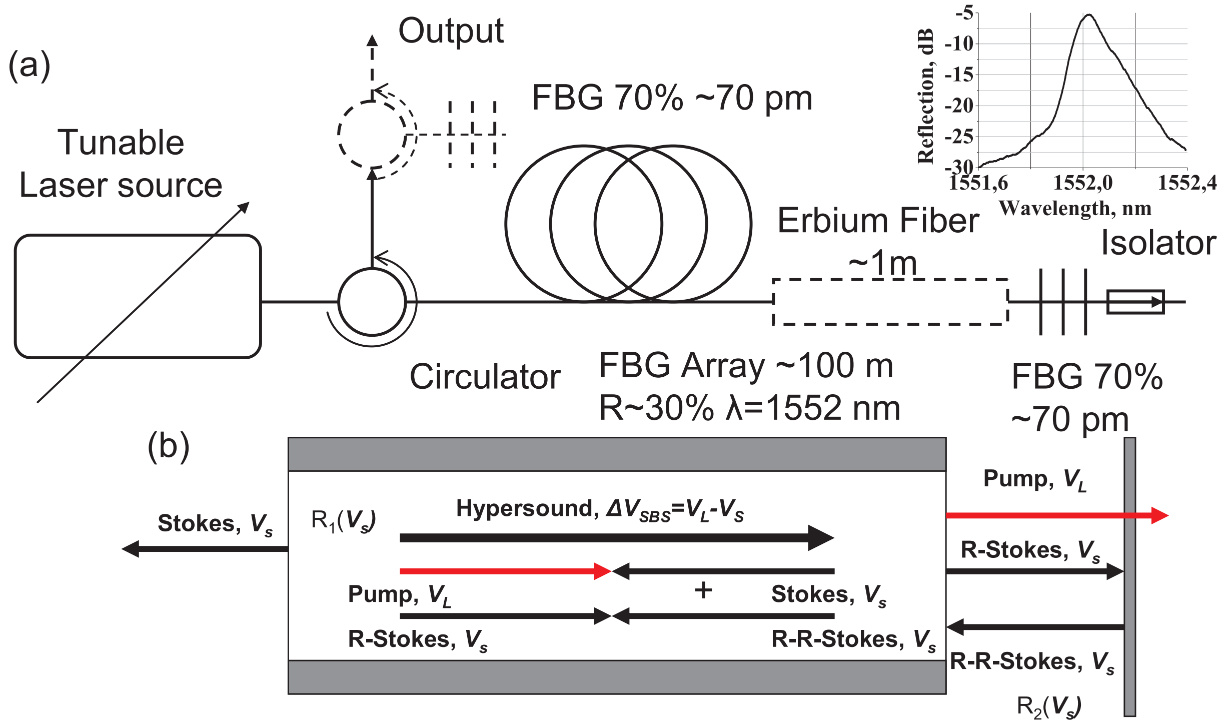

Fig. 1. Experimental setup (a). Interacting waves inside the fiber (b).

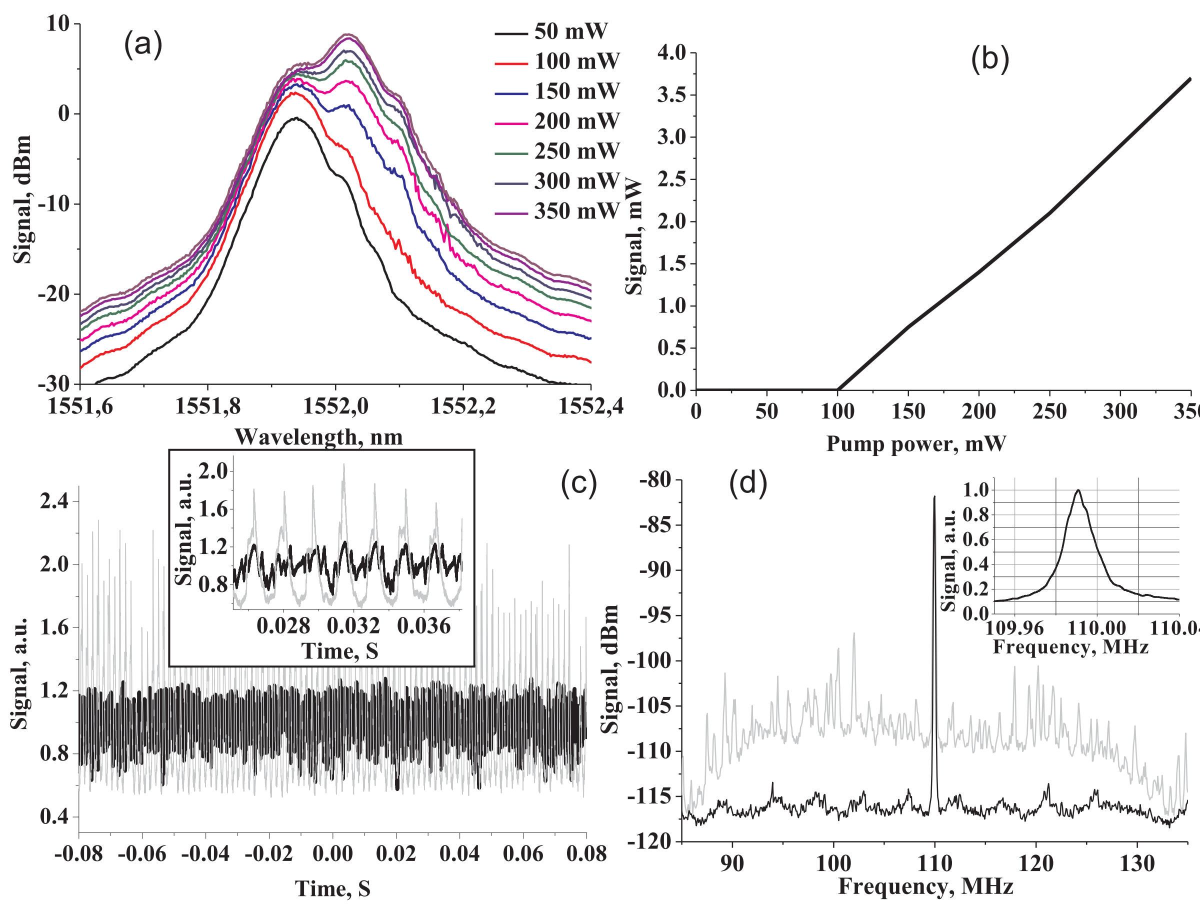

Fig. 2. Laser characteristics: optical spectrum (a), power (b), typical oscilloscope traces (c) and self-heterodyne spectrum (d) for laser configuration without (grey curves) and with (black curves) Er-doped fiber.

contribute to the SBS process. However, this wave reflected from FBG (R-R-Stokes) is amplified by the pump laser providing a coherent feedback to the initially generated Stokes wave. Thus a cavity consisting of a FBG with the reflectivity of $R_2(\nu_S) = 70\%$ and a distributed mirror is formed into the fiber. The effective reflection coefficient of the distributed fiber mirror is $R_{1eff}(\nu_S) = R_1(\nu_S)/GP_0L$ [9], where G is Brillouin gain factor, P_0 is the power of the pump laser, L is the fiber length. So, above the lasing threshold ($\exp(GP_0L)R_{1eff}(\nu_S)R_2(\nu_S) \sim 1$) one-pass Brillouin gain $\exp(GP_0L)$ in the 100-m optical fiber compensates cavity losses leading to Brillouin lasing in the fiber. This lasing is similar to cooperative Brillouin - Rayleigh process [10].

Fig. 2(a) shows the optical laser spectra recorded directly from the circulator output. They illustrate conversion of the optical power from the pump to the Stokes wave. Fig. 2(b) shows the average powers recorded at the fiber laser output. One can see that the Brillouin lasing threshold is achieved at 100 mW pump power. However, the most efficient pump-to-Stokes wave power conversion occurs at the maximal pump power level of 350 mW leading to generation of the maximum output power of 3.75 mW. Within the range of pump power levels between 150 and 350 mW the laser demonstrates dynamical features similar to those reported earlier for 25-km Brillouin random laser [4]. The recorded oscilloscope traces of the Stokes power shown in Fig. 2(c, grey curve) exhibit fluctuations around average level highlighting superposition of Brillouin lasing and Brillouin noise induced in the fiber configuration. The typical standard deviation of the output power fluctuation is estimated to be ~0.25. Fig. 2(d, grey curve) shows the self-heterodyne RF spectrum of laser radiation measured by RF analyzer (FSVR13, Rohde & Schwarz) through ~25 km unbalanced Mach-Zehnder interferometer comprising ~110 MHz electro-optic modulator. The spectrum comprises a number of peaks associated with fiber cavity modes of different orders. The typical spacing between the peaks is ~1 MHz that corresponds to FSR associated with the fiber cavity length of 100 m. The typical linewidth of the main peak is ~100 kHz.

Implementation of a piece of low-concentrated Er-doped fiber into the fiber cavity (Fig. 1a) drastically improves the laser operation stability. In particular, it causes suppression of the output power fluctuation (Fig. 2c, black curve). The minimum of the standard power deviation of the output power is obtained at the pump power level of ~250mW and evaluated to be ~0.1. The effect is associated with nonlinear filtering caused by an inscription of the dynamical population inversion grating during lasing at the Stokes frequency ν_S that filters out the laser radiation side modes [11,12]. The measured self-heterodyne RF spectrum of the laser radiation is shown in Fig. 2(d) by black curve. One can see that the side band components are suppressed by ~20 dB in comparison with the spectrum measured for the configuration without Er-doped fiber. The inset of Fig. 2(d) demonstrates the central peak of the spectrum. It has a clear Lorenzian shape with a width of 18 kHz highlighting the optical spectrum width for the laser generation to be 9 kHz.

In conclusion, we have observed Brillouin random lasing in short fiber cavity built from Bragg grating array fiber. The lasing occurs due to feedback caused by reflection from the 70% FBG and weak FBGs uniformly distributed over the fiber length. Implementation of the low-concentrated Er-doped fiber into the fiber cavity leads to significant improvement of the laser stability and narrowing of the laser generation linewidth down to ~9 kHz. With the reported features the laser could be a simple, compact, and cost effective solution for many practical applications.

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